(51) International Patent Classification 6 : H02J 3/24	A1	(11) International Publication Number: **WO 96/19025**
		(43) International Publication Date: 20 June 1996 (20.06.96)

(21) International Application Number: PCT/US95/16494

(22) International Filing Date: 14 December 1995 (14.12.95)

(30) Priority Data:
08/366,646   14 December 1994 (14.12.94)   US

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(81) Designated States: AL, AM, AT, AU, BB, BG, BR, BY, CA, CH, CN, CZ, DE, DK, EE, ES, FI, GB, GE, HU, JP, KE, KG, KP, KR, KZ, LK, LR, LS, LT, LU, LV, MD, MG, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SI, SK, TJ, TT, UA, UZ, VN, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG), ARIPO patent (KE, LS, MW, SD, SZ, UG).

Published
    With international search report.
    Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: SERIES COMPENSATOR INSERTING REAL AND REACTIVE IMPEDANCE INTO ELECTRIC POWER SYSTEM FOR DAMPING POWER OSCILLATIONS

(57) Abstract

A series compensator (11) for damping power oscillations in an electric power transmission system (1) includes a switching power converter (13) which injects a voltage into the transmission line (5) having a phase angle relative to transmission line current which is controlled to provide reactive compensation and to inject virtual real impedance into the line. The switching power converter (13) is a dc to ac converter which is capable of injecting virtual real impedance into the transmission line by virtue of the fact that it has a power exchange device (27) connected to its dc terminals (29). Where the power exchange device (27') is a resistor (37), the switching power converter (13) is capable of absorbing real power during surges in power on the line (5). Alternatively, the power exchange device (27) is a storage device (31) such as a battery bank or a super conducting magnet, in which case the switching power converter (13) can provide both virtual positive and negative real impedance.

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SERIES COMPENSATOR INSERTING REAL AND REACTIVE IMPEDANCE INTO ELECTRIC POWER SYSTEM FOR DAMPING POWER OSCILLATIONS

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to apparatus for damping power oscillations in electric power systems. More particularly it relates to a series compensator which can insert both real and reactive impedance into a transmission line to dampen the

5   power oscillations.

Background Information

Power oscillation frequently occurs in electric power systems due to disturbances, such as transmission line faults, line and load switchings, equipment failures and other events causing rapid system changes. Such power oscillation has

10   the undesirable effect of limiting the maximum transmittible power in the system. U.S. patent number 5,198,746 discloses a solid-state series compensator that injects a controllable, 60 Hz voltage in quadrature with the transmission line current. This injected voltage has the same compensating effect as that obtained with a variable capacitor, or inductor, connected in series with the line. The damping of the power

15   oscillation is achieved by appropriate modulation of the effective 60 Hz reactive impedance that the compensator injects in series with the line. That is, when the power in the line is increasing, as a result of acceleration of the power generator at the "sending-end" of the line and the consequent increase of the transmission angle, the capacitive impedance of the compensator is increased by increasing the

20   magnitude of the inserted 60 Hz voltage that lags the line current by 90 electrical degrees, in order to increase the degree of series compensation and thereby the

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transmittable power. Conversely, when the power in the line is decreasing, as a result of the deceleration of the "sending-end" generator and the consequent decrease in the transmission angle, the inserted voltage is made to lead the line current in order to create, in effect, an inductive output impedance and thereby to
5   increase the overall inductive impedance of the transmission line.

The series compensator of patent number 5,198,746 utilizes a dc to ac converter to generate the quadrature voltage. The ac terminals of the inverter are connected in series with the transmission line through a coupling transformer. A capacitor connected across the dc terminals provides the dc input voltage for the
10   converter. As the converter is theoretically only exchanging reactive power with the transmission line, there is no power drain on the capacitor. However, there are in reality losses in the switching circuits of the inverter. The real power needed to make up for these losses is provided by generating the compensating voltage at a phase angle slightly less than 90°.

15   U.S. patent number 5,343,139 discloses a generalized power flow controller for controlling the flow of power through the transmission line on a sustained basis. This power flow controller also utilizes a dc to ac inverter which injects a voltage in series with the transmission line voltage. However, the phase angle of the injected voltage relative to line current is not limited to substantially
20   90° as in the case of the compensator of U.S. patent number 5,198,746, but is controllable to any phase angle between 0 and 360°. The particular phase angle and the magnitude of the injected voltage may be selected to adjust any or all of the transmission line effective impedance, the effective phase angle between voltages at the two ends of the transmission line, and transmission line voltage
25   magnitude. This results in the adjustment of both real and reactive line impedance.

Real power needed to adjust the real component of impedance is provided to the dc to ac converter by an ac to dc converter having its ac terminals connected in shunt to the transmission line and its dc terminals connected to the dc terminals of the compensator converter through a dc link which includes a capacitor. The response of this flow controller is rapid enough that it can provide dynamic control of power flow, and it is also suitable for damping oscillation which may develop in the power system. However, this equipment designed primarily for power flow control, is more complex and expensive than the series compensator described in U.S. patent number 5,198,746.

There is a need for improved compensator for damping oscillations in electrical power systems.

More particularly, there is a need for such an improved compensator which can provide real power modulation as well as reactive power modulation to damp out power system oscillations.

SUMMARY OF THE INVENTION

These needs and others are satisfied by the invention which is directed to enhanced apparatus for providing series compensation to dampen out oscillation in an electric power transmission line which provides both real power and reactive power exchange with the power system. A particular feature of the invention is that it can provide injection of virtual positive real impedance in series with the transmission line to absorb real power as the generator accelerates during power oscillations. During those periods of the oscillation when the real power on the transmission line decreases, virtual negative real impedance is inserted in series with the transmission line to supply real power to the system. The virtual positive real impedance can be provided by a resistor which is selectively connected to absorb real power from the transmission line, and the virtual negative real impedance, which provides real power, can be provided by an energy storage device. The energy storage device, such as a battery or a super conducting magnet, can be used to supply both the virtual positive real impedance by absorbing real power, and the virtual negative real impedance by supplying real power. The virtual positive and negative real impedances are injected into the transmission line together with reactive compensation. A switching power converter generates a compensation voltage having a magnitude and a phase angle relative to

transmission line current which provides the required reactive and virtual real impedances. This voltage is injected in series with the transmission line voltage through a coupling transformer.

The switching power converter generates both the positive and negative reactive power required internally. The real power is supplied and absorbed by power exchange means connected to the dc terminals of the switching power converter.

It is not necessary that both positive and negative real impedance be provided, although more precise control can be effected through injection of both positive and negative real impedance into the transmission line. The fact that it is not necessary in accordance with the invention to inject both positive and negative real impedance into the transmission line is advantageous because providing positive impedance is easier and less costly than providing negative real impedance.

More particularly, the invention is directed to:

Apparatus for providing series line compensation with enhanced capability to dampen oscillations in an electric power transmission line carrying ac current at a selected transmission line voltage and fundamental frequency, said apparatus comprising:

compensation means coupled in series with said transmission line injecting into said transmission line a compensation voltage at said fundamental frequency with controllable magnitude and phase angle relative to said ac current in said transmission line;

power exchange means selectively connected to said transmission line only through said compensation means; and

control means controlling the controllable magnitude and phase angle of said compensation voltage to insert selected reactive and virtual real impedance into said transmission line to dampen said oscillations, and selectively connecting said power exchange means to said compensation means to enable said compensation means to provide said virtual real impedance.

BRIEF DESCRIPTION OF THE DRAWINGS

A full understanding of the invention can be gained from the following description of the preferred embodiments when read in conjunction with the accompanying drawings in which:

Figure 1 is a schematic diagram of a simple power system.

Figure 2 is a plot of electric power transmitted versus transmission angle for the power system shown in Figure 1.

Figure 3A is a schematic diagram of a portion of the power system of Figure 1 incorporating the present invention.

Figure 3B is a phasor diagram illustrating the compensating voltage injected in accordance with the invention into the power system shown in Figure 1.

Figures 4A - 4D illustrate waveforms pertinent to an understanding of the operation of the invention.

Figure 5 is a schematic diagram of a series compensator for the electric power system of Figure 1 in accordance with one embodiment of the invention.

Figure 6 is a schematic diagram of a second embodiment of a series compensator for damping power oscillations in the electric power system of Figure 1.

Figure 7 is a schematic diagram of a generalized form of the series compensator of the invention for damping power oscillations in the electric power system of Figure 1.

Figure 8 is a block diagram of the series compensator in accordance with the invention.

Figure 9 is a block diagram of an internal control for the series compensator of the invention.

Figure 10 is a block diagram illustrating in more detail portions of the internal control system of Figure 9.

DESCRIPTION OF THE PREFERRED EMBODIMENT

The subject invention is directed to a novel series compensator for damping power oscillations in electric power systems. In order to explain the proposed operation and control of this novel series compensator reference is made to the simple power system shown in Figure 1. This system 1 consists of a sending-

end generator 3, a transmission line 5, represented by its series inductive impedance, X, and a receiving-end power system 7 that can be considered as a power bus of infinite capacity. If the voltage phasor at the sending-end of the transmission line 5 is s and that at the receiving-end is r, then the transmitted

5   electric power, P_e, can be expressed by the following equation:

$$P_e = \{V_s \cdot V_r/X\} \sin \delta \qquad \qquad \text{Eq. (1)}$$

where Vs and Vr are the magnitudes of $\tilde{V}_s$ and $\tilde{V}_r$, respectively, and δ is the

angle between $\tilde{V}_s$ and $\tilde{V}_r$. The power P_e is shown plotted at fixed V_s, V_r, and X

against angle δ in Figure 2. It can be observed that the maximum transmittable

10   power is

$$P_e \, max = V_s \cdot V_r/X \qquad \qquad \text{Eq. (2)}$$

obtained at δ = 90 degrees.

In present power systems the power generator 3 is a rotating electro-magnetic machine that converts the mechanical input power P_m, usually provided

15   by a steam or gas turbine 9, into the electric power P_e feeding the transmission line 5. Under steady-state operating conditions, the mechanical input power P_m is equal to the electrical output power P_e (neglecting losses), and the turbine-generator set 3,9 runs at a constant speed such that a constant transmission angle δ_o, necessary to satisfy the $P_m = P_e$ equilibrium, is maintained (see Figure 2). The

20   occurrence of power oscillation is due to the fact that, whereas the electric power P_e can be changed almost instantaneously in the transmission line (often by unforeseen and accidental events such as transmission line faults and equipment failures), the mechanical input power P_m can be changed only very slowly due to the nature of mechanical controls and the large inertia involved in the rotating

25   system. Therefore, in the event of a transmission line fault or other disturbances in the electrical power system 1, the generator 3 receives more mechanical input power than the electric power transmittable by the faulty transmission system. As a result, the generator 3 starts to accelerate and the transmission angle becomes

larger than the steady-state angle δ_o. The process of acceleration of course means that the surplus mechanical energy is being stored mechanically by the rotating inertia of the turbine-generator set. In order to re-establish the steady-state equilibrium after fault clearing, this stored energy must be absorbed from the rotating mechanical system. Depending on the overall Q (quality) factor of the total electro-mechanical system, the absorption of this surplus energy can take a number of oscillatory cycles during which the electric power in the transmission system may widely fluctuate. In some cases, when the total system has negative damping, the magnitude of the oscillation keeps increasing until the system protection shuts-down the disturbed generator.

It is clear that, in principal, the oscillatory energy can be eliminated from the affected system in two ways. One is by increasing and decreasing the transmitted power in sympathy with the acceleration and deceleration of the generator and thus in sympathy with the positive-going and negative-going swings of the electric power. The other one is to subtract directly the surplus energy from the transmission system when the generator accelerates and dissipate it or return it to the system, from a temporary storage, when the generator is in the declaration interval.

U.S. patent number 5,198,746 proposes a novel method for the implementation of only the first approach. That is, the series compensator is controlled to decrease the transmission line impedance, and thereby increase the transmitted power during the acceleration periods of the machine, and to increase the transmission line impedance, and thereby decrease the transmitted power during the deceleration periods. This is accomplished by injecting a voltage at the fundamental frequency (60 Hz) into the transmission line in quadrature with the current flowing in the transmission line. The injected voltage lags the current by 90° for capacitive impedance and leads it by 90° for inductive impedance. It is evident that the method of power oscillation damping described in patent number 5,198,746 is based on a one dimensional modulation of the output of the series compensator. That is, the injected voltage is kept essentially in quadrature with respect to the line current so that the power exchange between the series compensator and the ac system is substantially reactive.

Our invention is based on a two dimensional modulation of the output of a series compensator. That is, the phase angle between the injected fundamental (60 Hz) voltage and the transmission line current is chosen so as to force both reactive and real power exchange between the series compensator and the ac system. This is illustrated in Figures 3A and 3B. As shown in Figure 3A, the series compensator 11 injects a compensation voltage V_c into the transmission line 5 in series with the line voltage V_l through a coupling transformer 12. Figure 3B is a phasor diagram showing the injected voltage V_c, line current I_L, and system voltage V_{sys} phasors. It can be observed that the injected voltage phasor V_c has a component V_{Cl} that is in quadrature with the line current and another component V_{Cr} that is in-phase with the line current I_L. The quadrature voltage component V_{Cl} represents the virtual reactive impedance that the series compensator provides for the compensation of the reactive line impedance in the manner proposed by patent number 5,198,746. The real component of voltage V_{Cr} represents a virtual positive real impedance (resistor) or a virtual negative real impedance (power source) in series with the line.

The variation of either the injected reactive impedance or the injected real impedance in sympathy with the transmission angle variation is effective to achieve power oscillation damping. The mechanism of damping with reactive impedance injection is explained in detail in patent number 5,198,746 which is hereby incorporated by reference. It can be appreciated that, in addition to the increased power transmission provided by reactive series compensation, by injecting a real positive impedance (resistor) in the line at the time when the sending-end generator 3 accelerates due to excess mechanical power, part of the surplus real power is dissipated thereby helping to establish an equilibrium between the mechanical input power and the electric output power required for stable system operation. Similarly, the injection of a real negative impedance (in effect, a real power source) in the line, when the sending-end generator is unable to satisfy the momentary electric power demand and therefore it is decelerating, would clearly remove part of the burden from the generator and thus would help the stabilization of the system.

Generally, the overall approach proposed by this invention is to provide highly effective damping of power oscillations by injecting simultaneously both reactive and real impedance in series with the line. Both the reactive and real impedance are controlled in sympathy with the transmission angle (and the corresponding power) variation. The reactive impedance is controlled to increase the transmitted electric power when the sending-end generator accelerates and to decrease the transmitted power when the generator decelerates. The real impedance is controlled to be positive and thus consume real power when the generator accelerates and to be negative and thus generate real power when the generator decelerates.

The proposed method for damping power oscillations in power systems is illustrated in Figures 4A - D, where the transmission angle δ, the transmitted electric power 9, and the reactive X_c and real R_c outputs, respectively, of the series compensator controlled between its maximum virtual capacitive and inductive impedance values and, respectively, the maximum virtual positive and negative real impedance values, are shown plotted against time. The dotted lines in the plots of the transmission angle and transmitted power represent an undamped oscillation while the solid lines illustrate the effect of damping in accordance with the invention. It should be noted that the variation of the real (or reactive) output between the maximum positive and maximum negative values is not a necessary requirement for effective damping. For example, effective damping can be achieved even if the inserted real or reactive impedance is varied between zero and a positive or negative maximum. As will be discussed, this is an important practical consideration because the implementation of a series compensator capable of injecting a virtual positive real impedance, in addition to a capacitive or inductive reactive impedance, is relatively simple and inexpensive, whereas the implementation of one that can also inject a virtual negative real impedance is relatively complex and expensive. The latter case in which only virtual positive real impedance is provided is illustrated in Figure 4D where the virtual negative real impedance is shown in dashed line.

As explained previously, the series compensator of the invention is able to inject concurrently a virtual reactive and a virtual real impedance in series with the line. The magnitude of these virtual impedances are independently

controllable within the VA rating limitation of the series compensator. This flexibility allows the selection of different operating modes for the series compensator under differing system conditions. Thus, various control strategies may be implemented to satisfy particular system requirements. In the preferred operating arrangement, the series compensator proposed is set up to provide reactive line compensation as the primary function to accomplish steady-state line impedance compensation and, in the case of parallel lines, line current equalization. However, whenever dynamic system disturbances are encountered, the series compensator can also execute the injection of a virtual real impedance in series with the line. The injected virtual reactive and virtual real impedances are controlled so as to maximize the electric load on the generator during its first and subsequent acceleration periods, and to minimize the electric load during the deceleration periods. This strategy provides maximum possible improvement in transient (first swing) stability and dynamic stability (oscillation damping) in addition to accomplishing the required steady-state line compensation requirements.

A series compensator capable of generating reactive and real impedance outputs in accordance with the invention is shown in Figure 5. The series compensator 11 includes a switching power converter in the form of a voltage-sourced dc to ac inverter 13 employing gate turn-off thyristors 15 (or other suitable power semi-conductor switches) to generate the ac voltage V_c required for real and reactive series compensation. The ac terminals 17 of the inverter 13 are connected to the coupling transformer 12 which in turn is connected in series in the transmission line 5. The transformer 19 and transmission line 5 are shown in single line for clarity of presentation; however, it will be understood that they represent three-phase implementation. A control 21 senses transmission line currents and voltages through current transformers 23 and potential transformers 25, respectively (again, multiphase for 3 three-phase system). The control 21 utilizes these currents and voltages together with parameter settings and control inputs to generate firing signals for the switches 15 in the inverter 13 to generate the appropriate instantaneous values of real and reactive impedance represented by the voltage V_c output by the inverter.

As discussed previously, the inverter 13 is capable of generating the virtual positive and negative reactive impedances internally. Real power to effect injection of virtual real impedance into the transmission line is provided by a power exchange device in the form of a real impedance source 27 connected to the dc terminals 29 of the inverter 13. In the embodiment of Figure 5, the real impedance source 27 comprises an energy storage device 31 and a dc to dc converter 33 providing charging and discharging control for the energy storage device. The energy storage device 31 can be, for instance, a battery bank or a super conducting magnet. In this case, the energy storage device absorbs real power from the transmission line 5 through the inverter 13 to insert virtual positive real impedance into the transmission line, and returns real power through the inverter 13 to the transmission line to provide virtual negative real impedance. A capacitor 35 connected across the dc terminals 29 stabilizes the dc voltage applied to the inverter 13.

Another embodiment of the invention is illustrated in Figure 6 wherein the real impedance source 27' comprises a resistive load 37 selectively connected across the dc terminals 29 of the inverter 13 by a switch 39 shunted by a fly back diode 41. This embodiment of the series compensator can supply both positive and negative reactive impedance, but only positive real impedance. However, it is considerably less expensive than the embodiment of Figure 5 and still provides substantially improved performance over the compensator of patent number 5,198,746 which only provides reactive impedance compensation.

A generalized embodiment of the invention is shown in Figure 7, where the power exchange device in the form of the real impedance source 27'' comprises a current source 43 which may be selectively connected by switch 45 to supply real power (negative real impedance) to the inverter 13, and a current sink 47 which is selectively connected by a switch 49 to absorb real power (provide positive real impedance) from the inverter 13. For purposes of analysis to be explained, the coupling transformer 12 is represented as voltage sources 51 a, b and c connected in each phase of the three-phase transmission line 5.

The functional operation of the series compensator 11 is accomplished by the appropriate control of the power inverter 13 producing the voltage injected in series with the line. Thus, the overall control system has two

major functions: one, referred to as the internal control function, is the synchronization and appropriate operation of the solid-state inverter 13 to generate the required voltage, with the proper magnitude and phase angle in relation to the line current, in series with the line to achieve the desired degree of reactive

5   impedance compensation and the real impedance insertion; the other, referred to as the external control function, is the determination of what reactive and real series compensation is needed (i.e., what magnitude and phase angle the inserted voltage must have) in order to provide the maximum improvement in transient stability and power oscillation damping.

10   The external control measures appropriate system variables, such as line voltages, currents, and frequency or rotational velocity, and derives reference signals for the internal control of the inverter. The operation and implementations of practical external control circuits related to the control of reactive impedance are described in patent number 5,198,746.

15   The operation of the external control circuits can be extended to the control of the virtual real impedance insertion, to achieve power oscillation damping, by the following simple rule. Whenever the series compensator is to inject a capacitive reactive impedance to increase the transmitted power, the compensator also injects a positive real impedance in series with the line to absorb

20   real power from the ac system. (This means that the power absorption from the accelerating generator is maximum -- the line transmits increased power due to the series capacitive compensation and the series compensator absorbs additional real power.) Conversely, whenever the compensator is to inject an inductive (reactive) impedance to decrease the transmitted power, the compensator simultaneously

25   injects a negative real impedance (if it has energy storage capability as shown in Figure 5) or zero real impedance (if it is equipped only with a switched energy absorbing device (resistor) as shown in Figure 6).

The internal control of the inverter is responsible for regulating the magnitude of the inverter ac output voltage and its phase angle in response to the

30   system requirements as determined by the external control. Figure 7 defines a polarity convention for each of the electrical variables that will be referred to in the following description of the internal control. In this simplified representation of Figure 7, the system power losses are neglected, and the inverter 13 is viewed

in a general way as a three-phase device whose terminal voltages appear in series with the transmission line. The leakage inductance of the power transformers 12 that couple the inverter into the line is shown as a nominal additional inductance 53a, b and c in series with the line.

In order to describe the internal control scheme, it is necessary to first define the mathematical model of the series compensator upon which it is based. The mathematical model uses the concept of instantaneous vectors to represent the three-phase voltage and current sets on the ac side of the inverter. Using this concept the three line currents are described instantaneously by a single vector with orthogonal components, i_{ds} and i_{qs}. The definition of i_{ds} and i_{qs} in terms of the actual line currents is as follows:

$$\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad \text{Eq. (3)}$$

$$\theta = \tan^{-1}(\frac{i_{qs}}{i_{ds}}) \qquad \text{Eq. (4)}$$

$$i = \sqrt{i_{ds}^2 + i_{qs}^2} \qquad \text{Eq. (5)}$$

In these equations 3-5, θ is the angle of the current vector relative to the ds-axis of the coordinate system, and i is the instantaneous magnitude of the current vector. In a similar way, the injected series voltages are represented vectorially in (ds, qs) coordinates and then further transformed to a rotating frame of reference (d, q) in which the d-axis is always coincident with the line current vector. This transformation of the voltage is defined as follows:

$$\begin{bmatrix} e_d \\ e_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{\pi}{3}) & \cos(\theta + \frac{\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{\pi}{3}) & -\sin(\theta - \frac{\pi}{3}) \end{bmatrix} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \qquad \text{Eq. (6)}$$

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In this reference frame the components of the series voltage vector, e_d and e_q account for the instantaneous real and reactive power drawn from the line respectively. The expressions for these power components are as follows:

$$\text{Real power (P)} = \frac{3}{2} \, i e_d \qquad\qquad \text{Eq. (7)}$$

5

$$\text{Reactive power (Q)} = \frac{3}{2} \, i e_q \qquad\qquad \text{Eq. (8)}$$

In Figure 8, these definitions are used to establish a block diagram of the series compensator (i.e., the system to be controlled.) In this diagram, the harmonic voltages generated by the inverter 13 are neglected and an instantaneous balance is assumed between the power at the ac-side and dc-side of the inverter.

10   A constant, K_I, defines the ratio between the dc capacitor voltage V_c and the peak phase voltage e_d, e_q on the ac-side of the inverter as shown at 53, 55, 57 and 59. A control angle, β, is defined as the angle by which the inverter voltage vector (i.e., the injected series voltage vector) leads the line current vector. This angle is set by the control system and can be changed rapidly and arbitrarily. As shown in

15   Figure 8, it sets the instantaneous value of the injected voltage at 53 and 57.

The ratio of e_q to the magnitude of the line current vector, i, constitutes the instantaneous "reactance" presented by the compensator to the line, and the ratio of e_d to i constitutes the instantaneous "resistance". It is further assumed that the line current is substantially determined by extraneous factors and

20   the current is therefore viewed as an independent input to the system.

In Fig. 8, the control angle, β, is seen to influence the inverter ac terminal power, P_{ac}, determined at 61 and 63 from e_d and the line current i directly through its effect on e_d as shown at 57 and 59. The inverter ac-side power is matched by an equal dc-side power that defines at 65 an instantaneous capacitor

25   charging current, i_1. An additional charging current, i_2, is provided by the dc real power source/sink 27. The sum of these charging currents is integrated by the capacitor 35 as represented at 67, bringing about a change in the dc capacitor voltage and hence a corresponding change in e_d and e_q.

Fig. 9 is a block diagram of the proposed internal control scheme. The external control 69 generates demands for reactance, X^*, and resistance, R^*, based on its observation of the transmission line conditions (determined from measurements of transmission line currents and voltages) and power system considerations. These are combined at 71 to form an impedance magnitude demand, Z^*. The reactance demand, X^*, and an adjusted resistance demand, R_1^*, are used to calculate the control angle, β. The impedance magnitude demand is multiplied at 73 by the magnitude of the line current vector, i, to obtain the magnitude of the desired series voltage, e^*. Since the magnitude of the dc capacitor voltage, V_c, directly determines the magnitude of the series ac voltage, a feedback control loop 75 is provided to regulate the value of V_c. An error signal is computed at 77 from as the difference between e^* and V_c multiplied by a constant K_I at 79 and passed to a controller 81 which either activates the dc power source 43 or the power sink 47 as appropriate in order to correct any deviation from the desired dc capacitor voltage. In Fig. 9, this controller 81 is shown as a simple hysteresis (bang-bang) type, although linear controllers might be used in practice.

In addition to this main control action, additional action is provided to cover the possibility that only a power sink 47 or only a power source 45, but not both, are included. When the dc-voltage error signal exceeds a set magnitude limit, it produces an amplified signal at 83 that is converted to an impedance by dividing by the current at 85. The quotient is scaled at 87 and added at 89 into the resistance demand, R^*, to form the adjusted resistance demand, R_1^*. This ensures that real power can always be negotiated to and from the transmission line to regulate the dc voltage whenever the regulation cannot be achieved by the dc source and/or sink. In effect, this additional action will override the resistance demand from the external controls to the extent that it does not request more real power than the inverter can source or sink.

The angle, β, is added to the angle, θ, of the line current vector at 91 to obtain a total angle, ϕ, for the series voltage vector, which is used at 93 to

determine the state of the switches 15 in the inverter 13. The switch state selection is achieved by means of a look-up table of switch states that are stored sequentially and accessed solely as a function of ϕ, the desired angle of the series voltage vector. The contents of the look-up table are naturally different for the different possible inverter topologies and harmonic reduction schemes, but in all cases the input is an angle (ϕ) and the output is a set of switch states that are fed to the gate drive circuits that control the actual switching devices 15. The feedback signals, i and θ, are generated from actual current measurements. A vector phase-locked loop 95 calculates the angle θ from the orthogonal components i_{ds} and i_{qs} of the single vector representing the three phase current which is generated by a vector resolver 97 from the three phase currents. The orthogonal components i_{ds} and i_{qs} are also used by a vector magnitude calculator 99 to calculate the current magnitude i. Block 101 is a limiter that imposes a positive lower limit on magnitude i before it is passed to divider block 85. This prevents the output of block 85 from becoming too large.

Figure 10 illustrates in more detail, elements of the vector resolver 97, the vector phase-locked loop 95 and the vector magnitude calculator 99. The vector resolver 97 generates the real and imaginary components i_{ds} and i_{qs} of the current vector in the rotating reference system from the measured phase currents i_a, i_b and i_c. It accomplishes this by implementing Equation 3, above. The vector magnitude calculator 99 generates the magnitude i of the single current vector through implementation of Equation 5, above.

The angle θ of the line current is not obtained in the preferred embodiment of the invention by the arctangent calculation of Equation 4, but rather by means of the vector phase-locked loop 95 which closely tracks the angular rotation of the current vector represented by the components i_{ds} and i_{qs} provided by the vector resolver 97. The real component i_{ds} is multiplied at 103 by the sine of the angle θ derived at 105. This product is subtracted in the difference junction 107, from the product calculated at 109 of the imaginary component i_{qs} of the current and the cosine of the angle θ derived at 111. Proportional plus integral

control is applied to the difference at 113 and integrated at 115 to generate the angle θ.

The subject invention provides controllable series, reactive line compensation and a virtual real impedance insertion which result in dramatic improvement in transient stability and oscillation damping in an electric power transmission system.

While specific embodiments of the invention have been described in detail, it will be appreciated by those skilled in the art that various modifications and alternatives to those details could be developed in light of the overall teachings of the disclosure. Accordingly, the particular arrangements disclosed are meant to be illustrative only and not limiting as to the scope of invention which is to be given the full breadth of the claims appended and any and all equivalents thereof.

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What is Claimed is:

     1.   Apparatus (11) for providing series line compensation with enhanced capability to dampen oscillations in an electric power transmission line (5) carrying ac current at a selected transmission line voltage and fundamental frequency, said apparatus comprising:

     compensation means (13) coupled in series with said transmission line injecting into said transmission line (5) a compensation voltage at said fundamental frequency with controllable magnitude and phase angle relative to said ac current in said transmission line;

     power exchange means (5) selectively connected to said transmission line (5) only through said compensation means (13); and

     control means (21) controlling the controllable magnitude and phase angle of said compensation voltage to insert selected reactive and virtual real impedance into said transmission line to dampen said oscillations, and selectively connecting said power exchange means (27) to said compensation means (13) to enable said compensation means (13) to provide said virtual real impedance.

     2.   The apparatus (11) of Claim 1 wherein said power exchange means (27) comprises at least positive real impedance (37).

     3.   The apparatus (11) of Claim 2 wherein said positive real impedance means (37) comprises resistor means.

     4.   The apparatus (11) of Claim 1 wherein said power exchange means (27) comprises both positive and negative real impedance and wherein said control means (21) selectively connects said positive and negative real impedance means to said compensation means (13) to enable said compensation means to

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provide virtual positive real impedance and virtual negative real impedance to said transmission line.

5.   The apparatus (11) of Claim 1 wherein said power exchange means (27) comprises at least negative real impedance means.

6.   The apparatus (11) of Claim 1 wherein said power exchange means (27) comprises storage means (31) alternatively storing real power drawn by said compensation means (13) from said transmission line (5) during positive surges in power on said transmission line (5) and returning real power to said transmission line (5) through said compensation means (13) during negative surges in power during power oscillations on said transmission line (5).

7.   Apparatus (11) for providing series line compensation with enhanced capability to dampen oscillations in an electric power transmission line (5) carrying ac current at a selected transmission line voltage and fundamental frequency, said apparatus comprising:

switching power converter means (13) coupled in series with said transmission line (5) injecting into said transmission line (5) a compensation voltage at said fundamental frequency with controllable magnitude and phase angle relative to said ac current in said transmission line (5);

power exchange means (27′) including at least positive real impedance means (37); and

control means (21) controlling the controllable magnitude and phase angle of said compensation voltage to insert selected reactive and virtual real impedance into said transmission line (5) to dampen said oscillations, said virtual real impedance being supported by said power exchange means (27′) and said reactive impedance being generated within said switching power converter means.

8.   The apparatus (11) of Claim 7 wherein said positive real impedance means (37) comprises resistor means.

9.   The apparatus (11) of Claim 7 where said power exchange means(27″) comprises both positive and negative real impedance means (47, 43).

5   10.   The apparatus (11) of Claim 9 wherein said control means (21) alternatively connects said positive and negative real impedance means (47, 43) to said switching power converter means (13).

11.   The apparatus (11) of Claim 9 wherein said power exchange means (27) comprises storage means (31) absorbing real power from said 10   transmission line (5) through said switching power converter means (13) to provide positive real impedance during positive surges in power on said transmission line (5), and supplying real power to said transmission line (5) through said switching power converter means (13) to provide negative real impedance during negative surges in power on said transmission line (5).

15   12.   The apparatus (11) of Claim 11 wherein said storage means (31) comprises battery means.

13.   The apparatus of Claim 1 wherein said storage means (31) comprises superconducting magnet means.

14.   A method for providing series line compensation with 20   enhanced capability to dampen oscillations in an electric power transmission line (5) carrying ac current at a selected transmission line voltage and fundamental frequency, said method comprising the steps of:

coupling compensation means (13) in series with said transmission line (5) to inject into said transmission line (5) a compensation voltage 25   at said fundamental frequency with controllable magnitude and phase angle relative to said ac current in said transmission line (5);

selectively connecting power exchange means (27) to said transmission line (5) only through said compensation means (13); and

controlling the controllable magnitude and phase angle of said 30   compensation voltage to insert selected reactive and virtual real impedance into said transmission line (5) to dampen said oscillations, and selectively connecting

said power exchange means (27) to said compensation means (13) to enable said compensation means (13) to provide said virtual real impedance.

15.   The method Claim 14 wherein said step of selectively connecting said power exchange means (27) comprises selectively connecting resistor means (37) to said transmission line (5) only through said compensation means (13).

16.   The method of Claim 14 wherein said step of selectively connecting said power exchange means (27) comprises selectively connecting positive and negative real impedance means (47, 43) to said compensation means (13) to enable said compensation means (13) to provide virtual positive real impedance and virtual negative real impedance to said transmission line (5).

17.   A method of providing series line compensation with enhanced capability to dampen oscillations in an electric power transmission line (5) carrying ac current at a selected transmission line voltage and fundamental frequency, said method comprising the steps of:

coupling switching power converter means (13) in series with said transmission line (5) to inject into said transmission line (5) a compensation voltage at said fundamental frequency with controllable magnitude and phase angle relative to said ac current in said transmission line;

providing power exchange means (27) including positive real impedance means; and

controlling the controllable magnitude in phase angle of said compensation voltage to insert selected reactive and virtual real impedance into said transmission line (5) to dampen said oscillations, said virtual real impedance being supported by said power exchange means (27) and said reactive impedance being generated within said switching power converter means (13).

18.   The method of Claim 17 wherein said step of providing power exchange means (27) comprises providing energy storage means (31), and wherein said controlling step comprises controlling the magnitude and phase angle of said compensation voltage such that said storage means (31) absorbs real power from said transmission line (5) through said switching power converter means (13) to provide positive real impedance during positive surges in power on said transmission line (5), and to supply real power to said transmission line (5) through

said switching power converter means (27) to provide negative real impedance during negative surges in power on said transmission line (5).
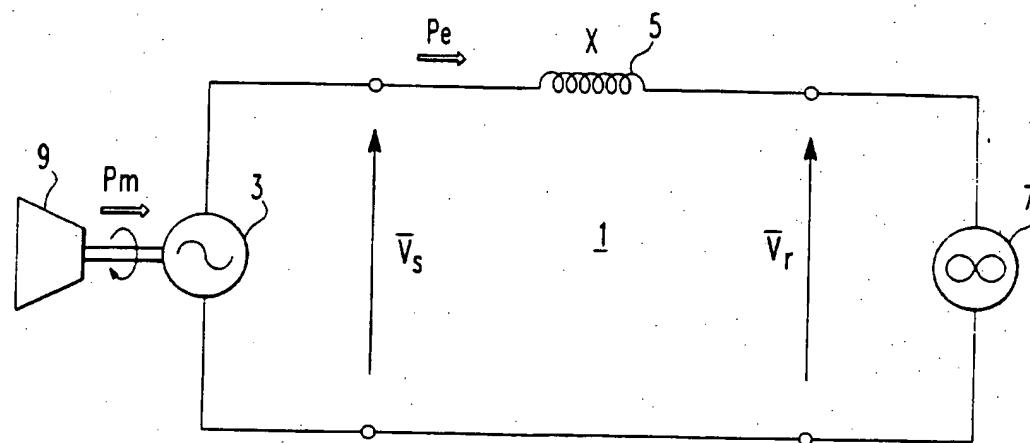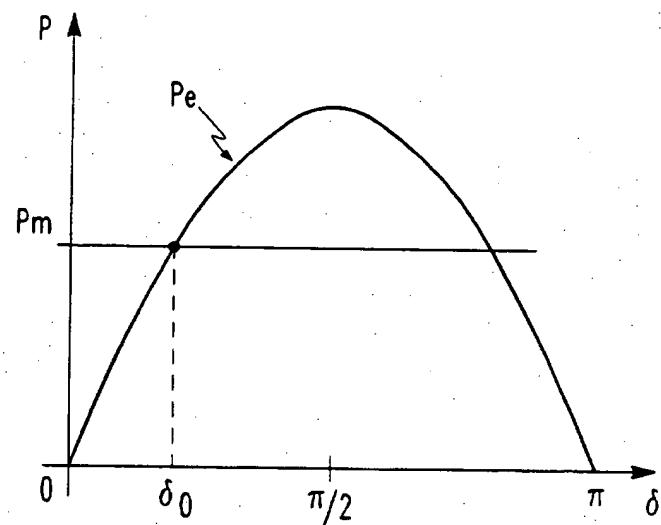
FIG.1

PRIOR ART

FIG.2

PRIOR ART

FIG.3A

FIG.3B
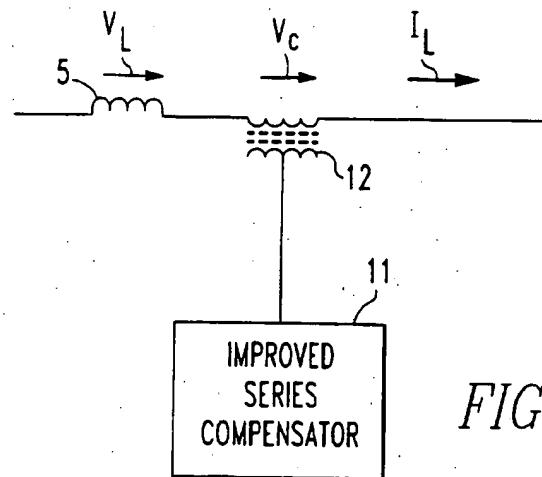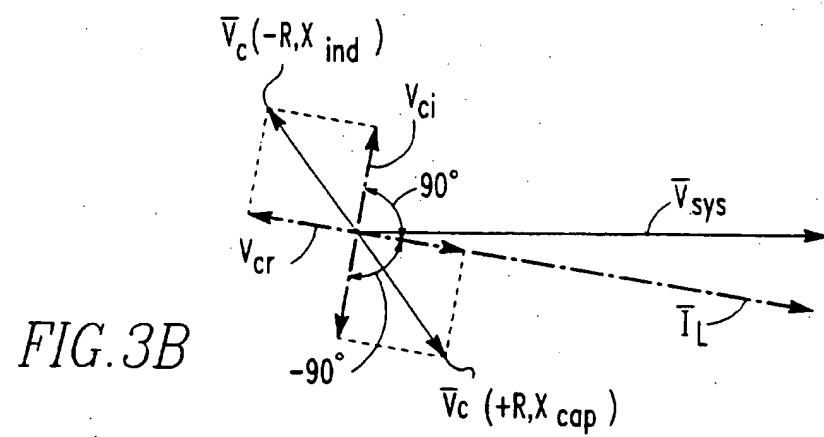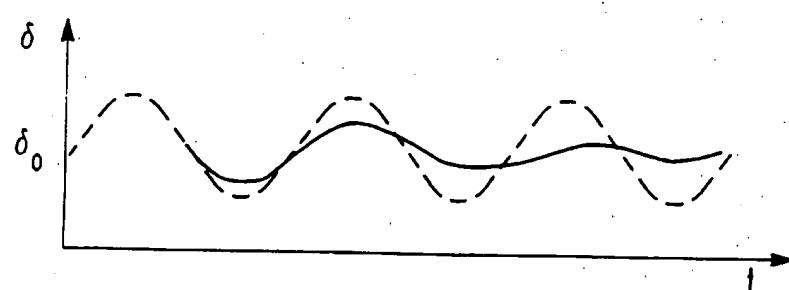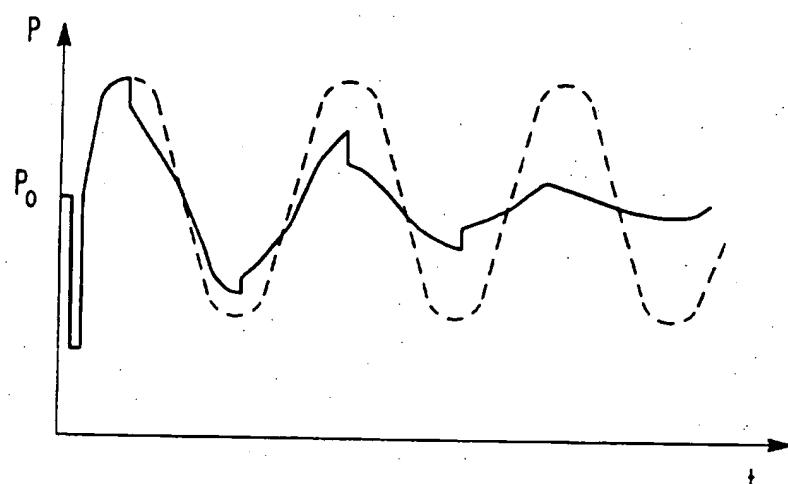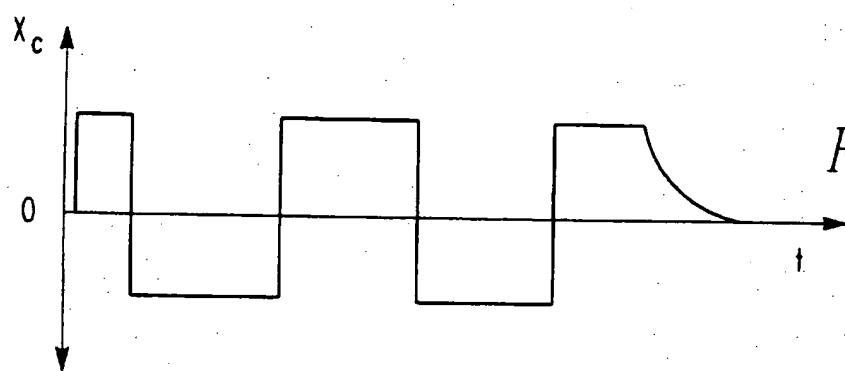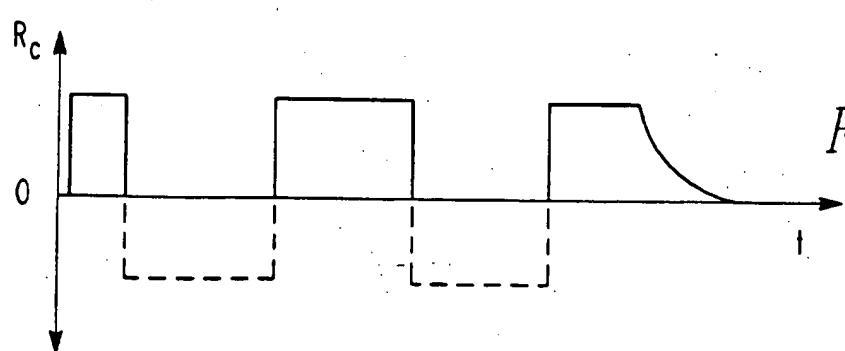
FIG.4A

FIG.4B

FIG.4C

FIG.4D
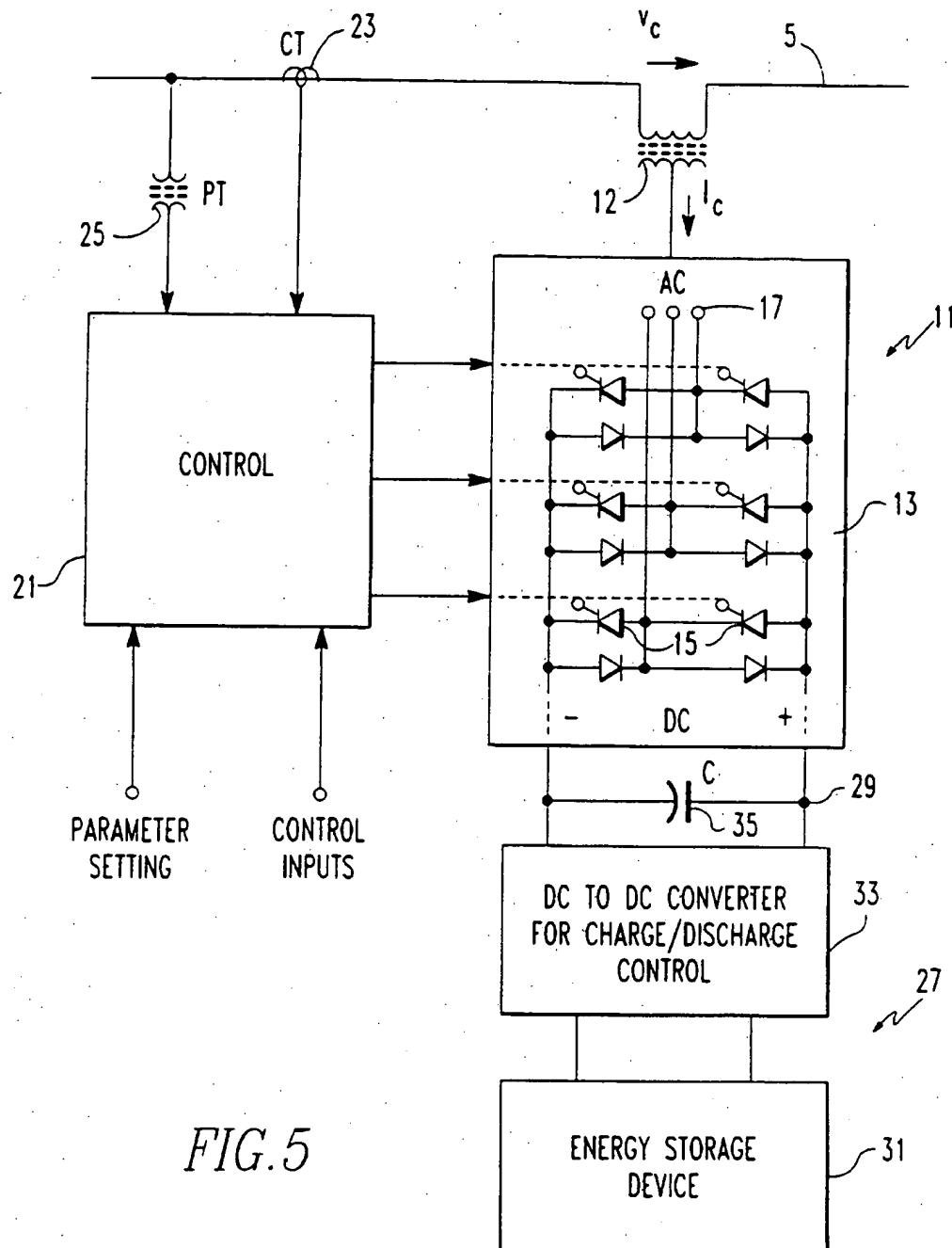
FIG.5
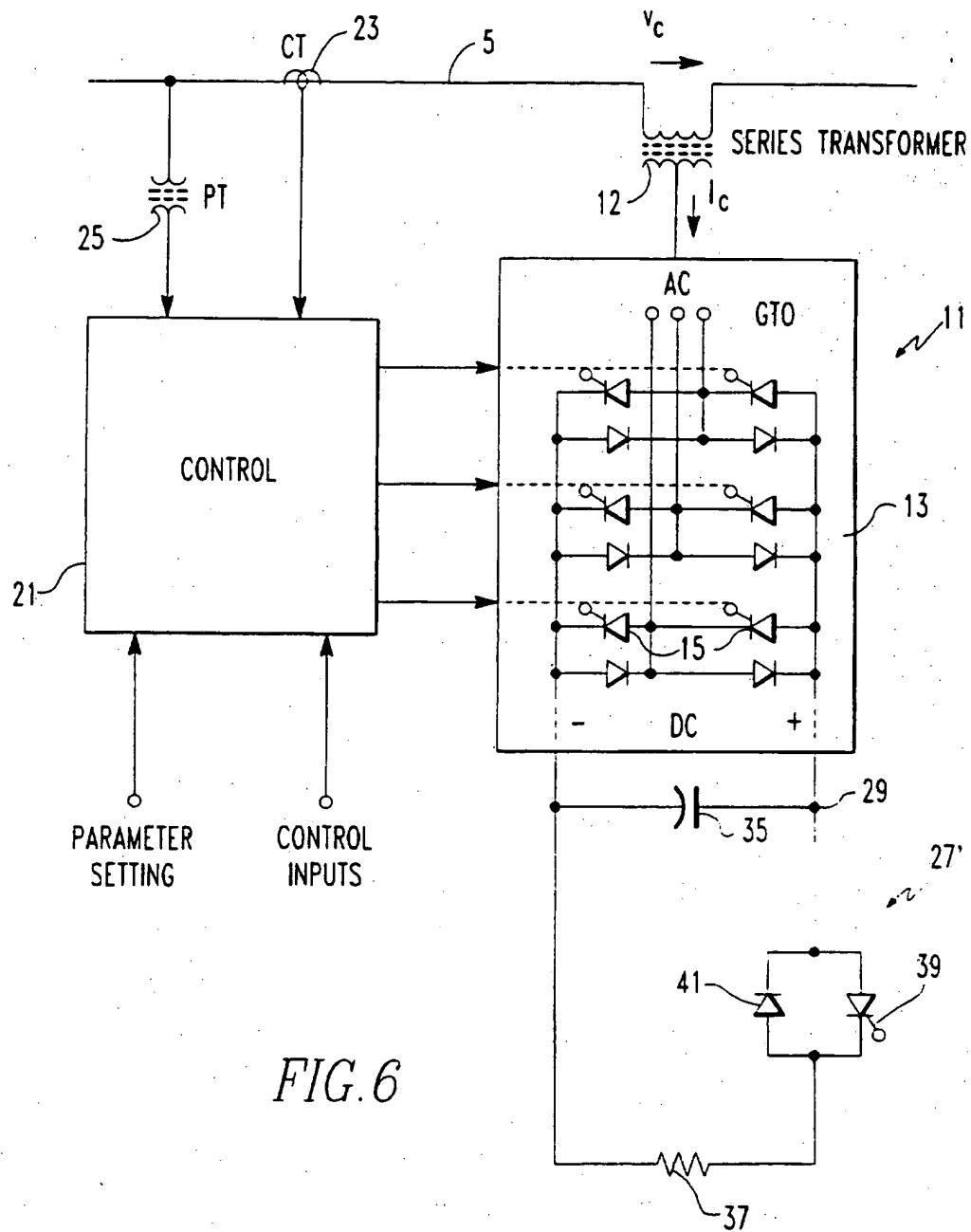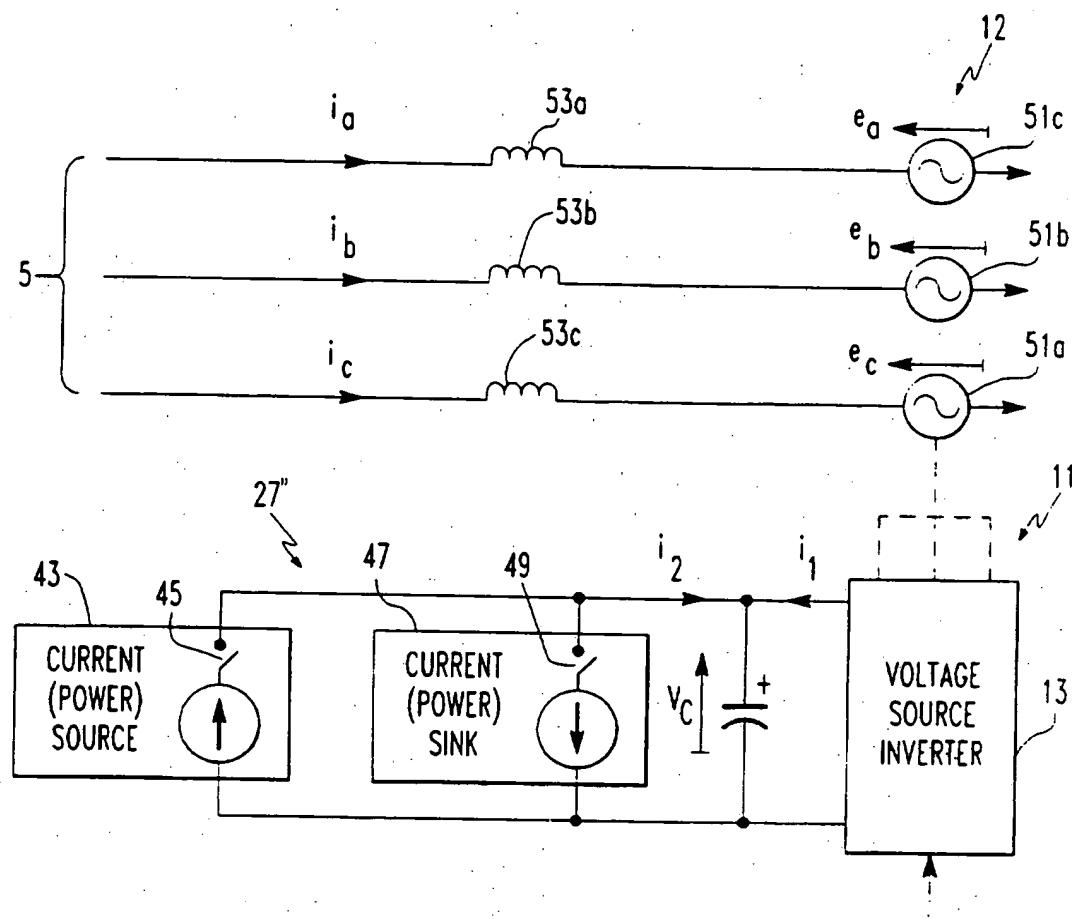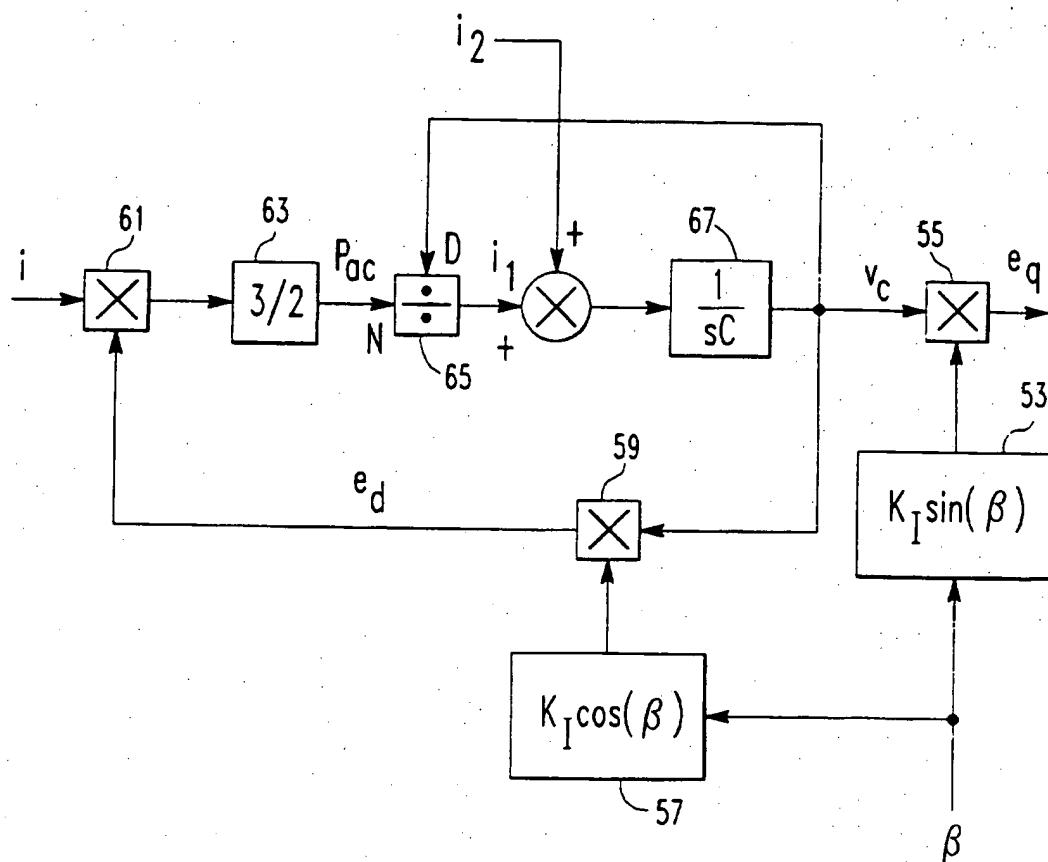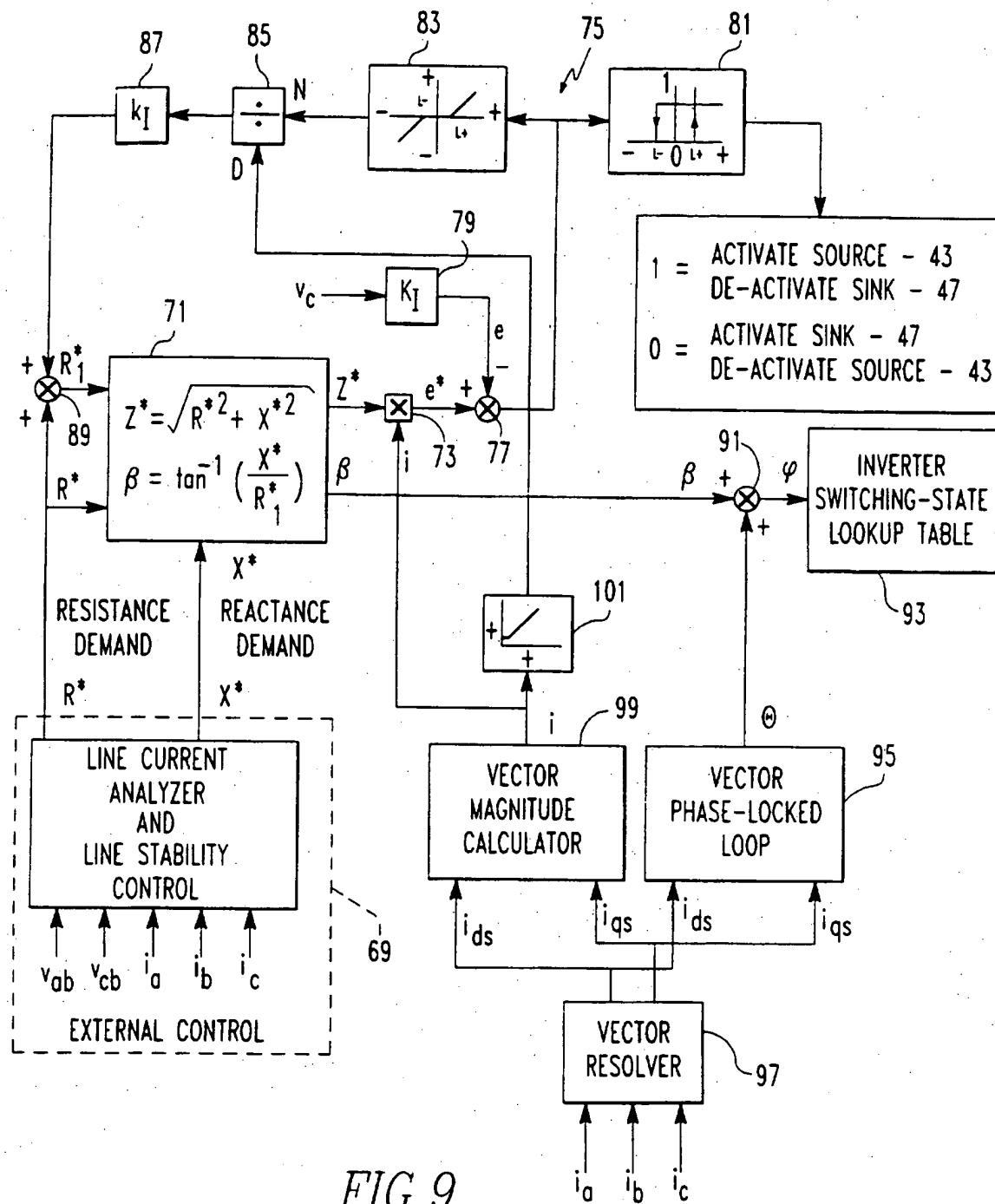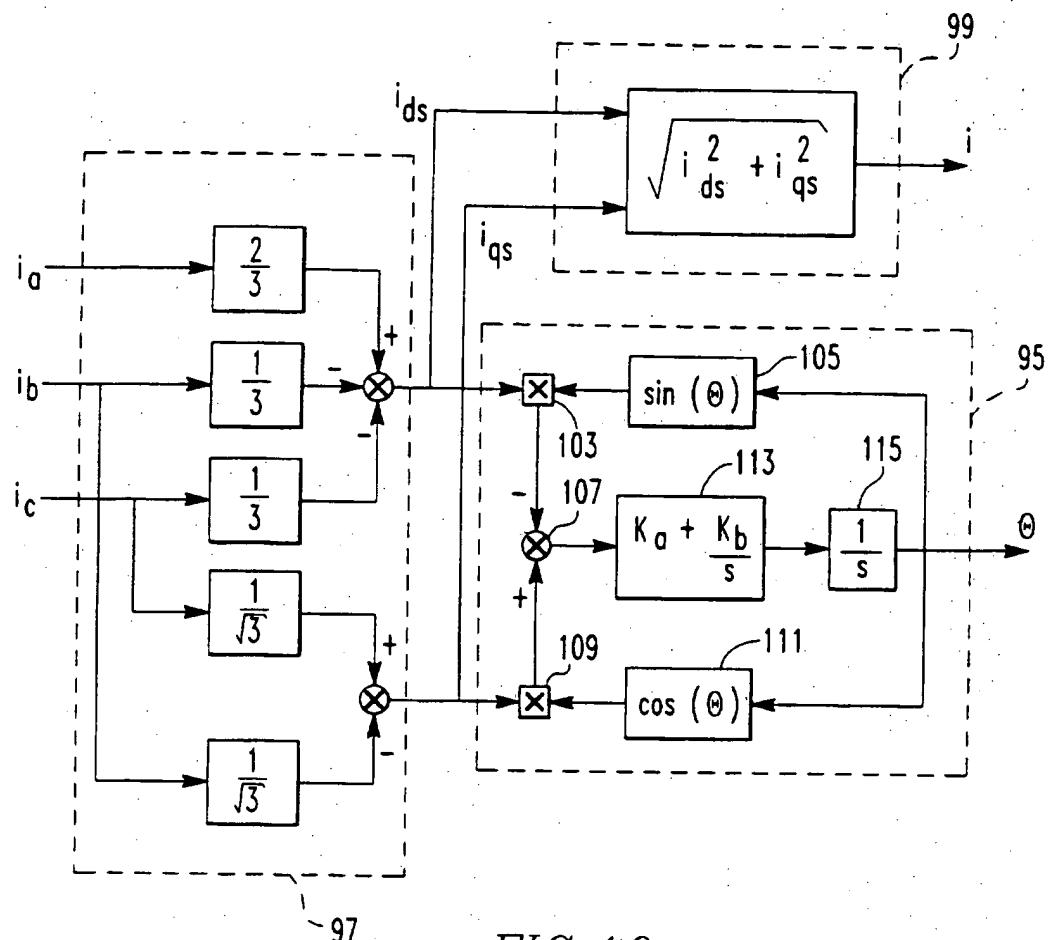
FIG.6

FIG.7

FIG.8

$FIG.9$

FIG.10

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6   H02J3/24

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6   H02J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US,A,5 198 746 (GYUGYI LASZLO ET AL) 30 March 1993 cited in the application see the whole document ---	1-18
A	US,A,5 343 139 (GYUGYI LASZLO ET AL) 30 August 1994 cited in the application see the whole document ---	1-18
A	PROCEEDINGS OF THE ANNUAL POWER ELECTRONICS SPECIALISTS CONFERENCE, TAIPEI, TAIWAN, JUNE 20 - 24, 1994, vol. 1, SOCIETY, pages 211-216, XP000492020 LOPES L A C ET AL: "A PWM QUADRATURE BOOSTER PHASE SHIFTER FOR AC POWER TRANSMISSION" ---	1-18

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[X] Further documents are listed in the continuation of box C.   [X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
29 April 1996	15.05.96

Name and mailing address of the ISA	Authorized officer
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page 1 of 2

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	IEE PROCEEDINGS C. GENERATION, TRANSMISSION, DISTRIBUTION, vol. 138, no. 5 PART C, 1 September 1991, pages 419-426, XP000262690 LEE Y S ET AL: "APPLICATION OF SUPERCONDUCTING MAGNETIC ENERGY STORAGE UNIT ON DAMPING OF TURBOGENERATOR SUBSYNCHRONOUS OSCILLATION". ---	1-18
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A	WO,A,93 03531 (ELECTRIC POWER RES INST) 18 February 1993 see abstract; figure 1 -----	1-18

1

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US-A-5343139	30-08-94	NONE		
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		AU-B-	2249292	02-03-93
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